FISHERY RESPONSES TO CHANGES IN OCEANIC CLIMATES: THE CASE OF THE OREGON OCEAN SHRIMP FISHERY

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ABSTRACT

Oregon ocean shrimp annual harvest relies on the successful recruitment and growth of age one shrimp. Changes in oceanic conditions appear to have major impacts on recruitment, spatial abundance and growth rates. Successful recruitment has been identified with the timing and strength of the spring transition generating oceanic conditions favorable for advection of shrimp to settling grounds. Similarly, changes in individual shrimp growth rates can be traced to decadal variability in Pacific environmental indicators. In turn, this environmental variability affects shrimp value as processors and markets seek larger and uniform shrimp. This paper examines how variable recruitment subject to environmental forcing influences the ocean shrimp, *Pandalus jordani*, fishery. Given the historical importance of this fishery to Oregon, opportunities to improve harvest value despite abundance variability are explored through alternative management strategies focusing on efficiency and stability. An optimization model analyses harvest strategies to achieve alternative sets of fishery objectives using a 22-year environmentally driven recruitment index, a 22-year commercial growth series, an ex-vessel size-price relationship, and fishery survey information. Environmentally driven and fishery driven stock recruitment are incorporated into the model to determine optimal dynamic seasonal and annual harvest patterns. Implications for long-term management of the fishery are discussed.

Keywords: recruitment, environmental conditions, shrimp, optimization, net present value

INTRODUCTION

A key characteristic of short-lived, highly variable fisheries is a common dependence on large ocean current systems. The seasonal upwelling cycle of the coastal Oregon region (North Eastern Pacific) is a combination of environmental cycles with differing time scales. Similar to cephalopod and anchovy populations, ocean shrimp show wide abundance fluctuations and are susceptible to changes in oceanographic conditions (Sauer et al., 2002). Oregon ocean shrimp experience advection from northwesterly winds in the spring and summer months off the Oregon coast (Hannah, 1993). The large, low pressure system off the Aleutian Islands (Aleutian Low), creates northward flowing winds along the Oregon coast in winter. This change in wind direction is known as the spring transition and is the indicator of the expected Summer upwelling along the Oregon Coast of which shrimp larvae depend.

Shrimp abundance may be affected by synchronous decadal oscillations such as the El Niño Southern Oscillation (ENSO) (Bakun and Broad, 2003). Figure 1 shows that recruitment and landings in the ocean shrimp fishery as they relate to the April Sea Level Heigh. Recruitment and landings tend to be poor following most El Niño events in the North Pacific (1982-83, 1986-87, 1991-92, 1993, 1994, 1997-98). Further, a Pacific Decadal Oscillation (PDO) has been identified (Stephens, et al., 2001; Ware, 1995) describing regime shifts in upper ocean and surface air temperatures and atmospheric sea level pressure. The last regime change that occurred in the North Pacific was in the mid-1970s. The post-1976 period shows increased temperatures consistent with the changes in shrimp growth rates over this period (Hannah and Jones, 1991). Shrimp CPUE has decreased but the individual growth rate of shrimp increased compared to the previous decade (1966-1976). Empirical data from 1978-1998 found age one shrimp to be fully recruited to the trawl gear by 15 months of age. Around 1998, another regime change is believed to have occurred, potentially resulting in ocean conditions similar to the pre-1976 period.[1]

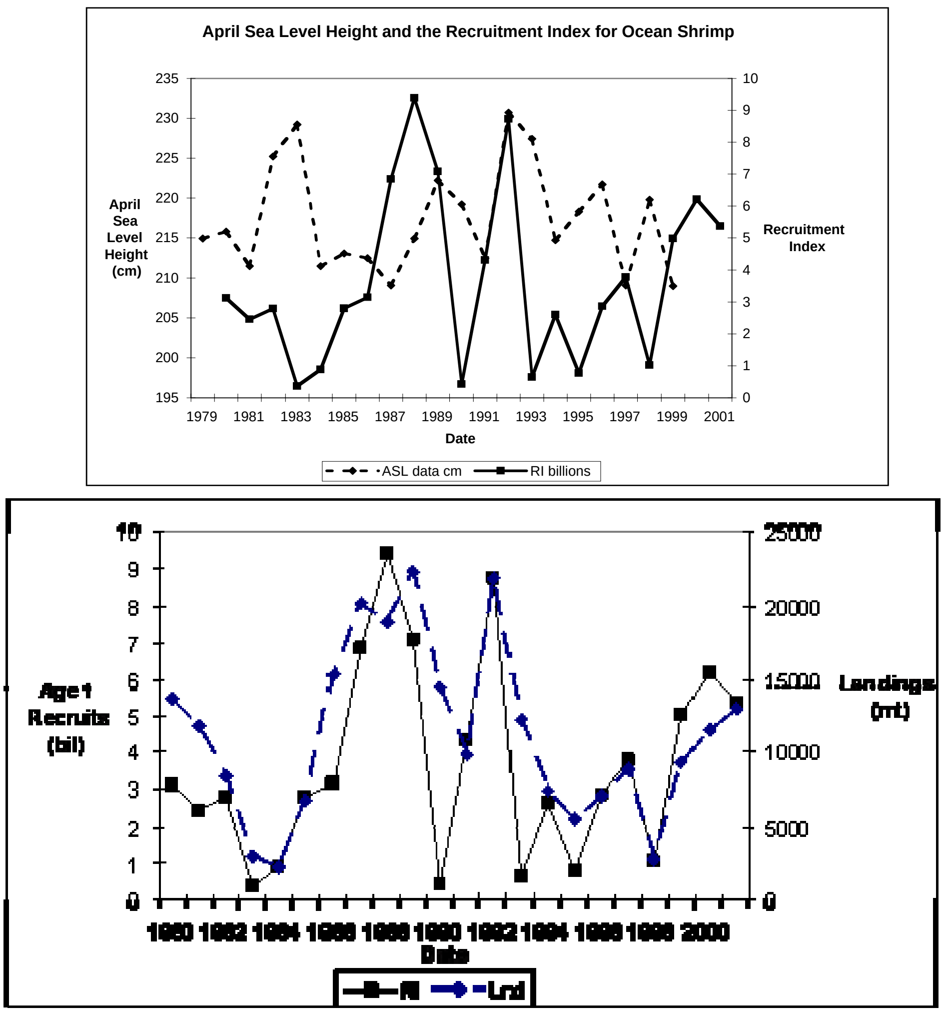

Figure 1. April Sea Level height, annual recruitment index of age 1 shrimp and landings.

[1] Hannah, R. W. and S. Jones. 2002. Annual Pink Shrimp Review. Oregon Department of Fish and Wildlife.

Environmental Variability Affecting Ocean Shrimp Recruitment

Shrimp recruitment success is recognized as an important indicator of expected future fishing conditions. The 30-year variation in the catch of ocean shrimp has ranged from as low as 2770 mt in 1998 to 48,000 mt in 1992 (PSMFC, 1990; OASS, 2003). A primary factor that influences ocean shrimp catch may be variation in survival from the early larval stages to the age of recruitment (Hannah, 1993). Early attempts to define a stock recruitment relationship did not take into account environmental variables. Hannah (1993) identified the April sea level height (ASL) as the best measurable environmental indicator for the occurrence of the spring transition, as elevated winter sea levels decrease during that month and remain low through the summer months. As the spring transition off the coast of Oregon typically occurs in mid-April, a switch from southwesterly to northwesterly winds drives the southward current (offshore surface flow with deeper water replacement) and ultimately produces localized upwelling. Hannah (1999) further substantiated the significant earlier correlation between recruitment and the April sea level height and suggested a preliminary stock recruitment relationship for ocean shrimp.

Ocean Shrimp Fishery and Management

The Oregon ocean shrimp fishery generates average annual revenues of $17 million or approximately 20% of Oregon's fishery revenues (OASS, 2002). Although many economic factors can influence ex-vessel prices, a key factor is the size of shrimp. Ex-vessel prices for shrimp are based on the count per pound (CPP) estimation from the landed catch. Results from an informal harvester and processor survey indicate that shrimp with a CPP less than 140 receive $0.15-$0.25 more than smaller shrimp with a higher count. Wholesale prices range from $3.00-$4.50 per pound, depending on finished count[2].

To address the significant variation in stocks and landings of ocean shrimp, some harvesters invest in a portfolio of fisheries. Permit portfolios allow shrimp harvesters to choose their fishery depending on economic conditions, resource availability and quota (Hilborn et al., 2001; Smith and McKelvey, 1986). As many as 175 shrimp permits are held by full and part-time shrimp harvesters, although in any year only a proportion of those vessels fish for shrimp**.**

Identification of reliable indicators of future recruitment would be valuable for improved management of highly variable fisheries. The ocean shrimp fishery has become a predominately recruitment-based fishery with 80-90% of the harvests composed of age one recruits. Figure 2 shows the 1999-2003 and 1994-1998 average age compositions for the fishery. The high proportion of age one shrimp in the catch, coupled with 50 years of fishing shrimp, reflect the persistent high effort imposed on the shrimp resource.

Economic efficiency is not explicitly defined in ocean shrimp management policies but is important to harvesters and processors. Efficiency, for the purposes of this research, is defined as net present value (the summation of annually discounted fishery profit). A discount rate of 5% was used that reflects the social discount rate in government transactions and is within the range investigated by Rowse (2000).

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[2] **Further details for ocean shrimp ex-vessel and wholesale prices are found in Gallagher et al., (in prep).**

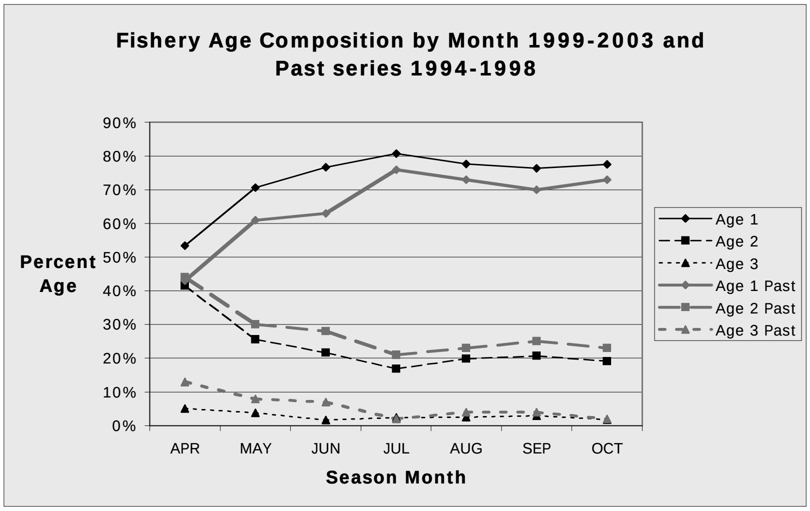

Figure 2. Average Age Composition of Shrimp Landed Catch from 1999-2003.

The present management strategy (allowing for the escapement of age 1 shrimp) is unlikely to decrease variability in shrimp abundance and may not increase average shrimp recruitment. A strategy that can decrease or eliminate exploitation of all vulnerable age classes once a failed year class has been forecasted may generate increased recruitment (Hannah, 1999). Such a strategy may also require a reduction in capacity of the present fishery.

METHODOLOGY

A bioeconomic optimization model developed for the ocean shrimp fishery (Gallagher et al., in prep) was modified to account for environmental recruitment processes in the production of new year classes. Model equations represent key environmental, biological and economic relationships (Tables 1 and 2). The relationships describing biological dynamics of ocean shrimp follow the generalized age structured model and are equivalent to a discrete time optimal control problem (Clark, 1990). The optimization problems were solved using the nonlinear control optimization solver (CONOPT) in the General Algebraic Modeling System (Jefferson and Boisvert, 1989).

The optimization model was constructed to maximize fishery objectives for net present value (NPV), by selecting the optimum timing and effort levels in the shrimp harvest each season. NPV was calculated as the sum of annual net benefits, (gross revenues minus variable costs) discounted at an annual rate, (r) over a 22-year time horizon. The monthly average level of shrimp fishery effort (at 12,000 single rig equivalent hours) and the observed range of monthly effort was used as the median level of monthly allowable effort in the optimization models. Natural and fishing mortalities were taken from averages estimated from commercial fishery data by Hannah (1995).

Table 1. Mathematical Model Notations, Descriptions[3] and Select Model Equations

Biological and Economic Parameters and relevant units:

q	catchability coefficient (initially fixed)	*avfc*	average fixed cost per vessel ($)
sel	selectivity	*opc*	opportunity cost per vessel ($)
rec	recruitment (billions)	*acpp*	monthly count per pound by age
wt	monthly weight at age (grams)	*tpm*	vessel trips per month
r	annual real discount rate (percentage)		
ni	standing stock (amount of shrimp in numbers for ages 2, 3, and 4)		
ms, mw	instantaneous natural mortality for summer April-October and winter months November-March by age		

Biological and Economic Variables:

N	number of shrimp (billions)	B	Biomass (metric tons)
Z	instantaneous monthly total mortality	VC	Variable costs ($ monthly)
F	instantaneous monthly fishing mortality	SHC	Crew share ($monthly sum trips)
C	harvest in numbers (catch in millions)	FUC	Fuel Cost ($monthly sum trips)
Y	harvest yield in pounds (conversion)	SUC	Supplies ($monthly sum trips)
MY	monthly yield (metric tons)	MC	Maintenance ($monthly sum)
TPS	trips	TVC	Total variable costs ($ annual)
NV	number of vessels	VFC	Variable monthly fixed costs ($)
E	effort - (single rig equivalent - hours)	TFC	Total fixed Cost ($ annual)
CPP	count per pound mixture of age classes	CST	Total annual costs ($)
EVP	ex-vessel price ($/lb.)	TY	Total Yield (mt)
RI	recruitment numbers (billions)	TR	Total Revenue ($)
SLH	sea level height (cm difference)	PRO	Monthly Profit ($)
SSN	spawning stock numbers (billions)	NPV	Net Present Value ($)

Indices:

y	years (2000, 2001…, 2012)	*s*	season months March through February
v	vessel types	*a*	age classes or cohorts (months) available for harvest

Base Model

Shrimp abundance:	$N_{y,s=1,a=1} = rec_y$
Interyear population dynamics:	$N_{y+1,s=1,a+1} = N_{y,s=12,a} \cdot e^{-Zy,s=12,a}$
Fishing mortality:	$F_{y,s,a} = SEL_{a=1,s} \bullet q_{y,s,a} \bullet E_{y,s}$
Monthly trip constraint (110 vessels):	$TPS_{y,s} \leq 330$
Effort:	$E_{y,s} = 0.000015 * TPS_{y,s}$
Shrimp Biomass:	$B_{y,s,a} = WT_{s,a} \bullet N_{y,s,a}$
Catch Weighted Count per pound:	$CPP_{y,s} = \sum_a (MY_{y,s,a} * ACPP_{s,a}) / \sum_a MY_{y,s,a}$
Harvest Numbers (Catch):	$C_{y,s,a} = (F_{y,s,a} / \mathbf{Z}_{y,s,a}) \cdot \mathbf{N}_{y,s,a} (1 - e^{-Zy,s,a})$
Catch per unit effort:	$CPUE_{ys} = Y_{y,s} / E_{y,s}$

Log Stock Recruit & SLH

$$LN(recruits)_{y+2,s} = 29.108 + 0.798*(LN(SSN_{y,oct})*1000000000))-11.203*SLH_{y+1}$$

Recruit Index Stock Recruit	$RI_{Y+2,S} = \exp(recruits_{Y+2,S})/1000000000$
Real ex-vessel price:	$EVP_{y,s} = .6349-.0015*(CPP_{y,s})-.1259*d1986$
Revenue:	$REV_{y,s} = EVP_{y,s} * Y_{y,s}$
Monthly variable cost:	$VC_{y,s} = FUC_{y,s} + SHC_{y,s} + SUC + MC$
Total variable costs of the fleet:	$TVC_{y,s} = TPS_{y,s} * VC_{y,s}$
Variable fixed costs:	$VFC_{y,s} = NV_{y,s} * 2.571$
Total fixed costs:	$TFC_y = \sum_s (VFC_{y,s})$
Total seasonal cost:	$CST_{y,s} = TFC_{y,s} + TVC_{y,s}$
Optimize net present value (NPV):	$Max\ NPV = \sum_y [(1/1+r)^y \cdot \sum_s (TR_{y,s} - TVC_{y,s})]$
Modifications to base equations (NPV)	$Max\ NPV = \sum_y [(1/1+r)^y \cdot \sum_s (TR_{y,s} - TVC_{y,s} - VFC_{y,s})]$

[3] Variables are depicted in upper case letters, parameters in lower case; subscripted lower case letters represent indices. Each component identifies (1) time succession in months, and (2) the age class of shrimp in years. Equations move the stock across months and years to advance the age of each cohort. Months are identified using a subscript, s = 1, 2, 3…12, and age classes by a = 1…4 to indicate shrimp age in years for the exploited population.

Environmental Variable and Preliminary Spawning Stock Relationship

The analysis incorporated the highly significant empirical recruitment relationship developed by Hannah (1999) that explained 74% of the variation in the log of shrimp recruits. Spawning shrimp available at the end of October (1 November) represent the end of the time-period in the estimated relationship. Age 1 recruitment numbers (in billions) were constrained between a low of 0.2 and a high of 9.0 billion shrimp that would enter the fishery beginning in April. The model builds on the premise that harvesters do consider net revenue as a primary factor in making fishing decisions. Based on the previous findings from Gallagher et al., (2005) and Gallagher et al, (in prep), fishing timing and intensity while optimizing for net present value (NPV), generate the highest catch rates and most valuable shrimp.

Reduced Fishing Effort

The sea level height stock recruitment (SLHSR) optimization model was systematically modified to consider reductions in monthly fishery effort to evaluate parameters of interest and results were compared with the base SLHSR model. Non-biological indicators of variability in the ocean shrimp fishery include monthly and seasonal trips, harvest yield and revenue generated by the fishery. Actual shrimp season landings (trips) from 1980-2000 show a decline in overall effort since the late 1980s. Although the monthly average effort (converted to trip effort for comparison) in the 1980s and early 1990s ranged from 230-450 trips per month, more recent effort levels (1997 through 2003) ranged from 92-217 trips per month. A stability index, as measured by the coefficient of variation, was calculated for monthly and seasonal indicators and compared to the base SLHSR model.

Figure 3 shows the average monthly historical fishing effort in the ocean shrimp fishery expressed as trips per month. The upper limits of effort shown in the graph correspond to the 8000 to 16000 monthly single rig equivalent hours exerted in the fishery. A conservative level of 50% gear elemental efficiency computes trip effort to the instantaneous levels of fishing mortality (F=0.12 to F=0.24).

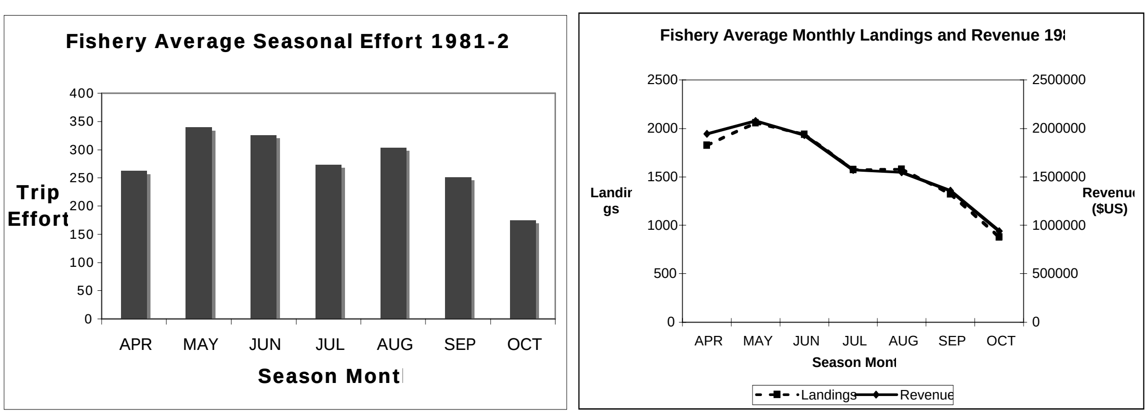

Figure 3a and 3b. Ocean Shrimp Average Monthly Fishing Effort, Landings and Revenue.

In the ocean shrimp fishery, seasonal landings and revenue reflect shrimp abundance and fishery performance (Figure 4). The annual moving average for fishery revenue is presently $11.3 million, with monthly average revenue values ranging from $1 – 2.5 million. Annual average catch in the ocean shrimp fishery is 11,435 metric tons (mt)[4]. Annual catch has ranged from a high of a high of 22,284 mt in 1989 to a low of 2764 mt (in 1998). Fishery annual revenue has averaged $11.3 million, ranging from $30.3 million in 1987 to $3.2 million in 1998. The intra seasonal pattern of revenue reflects the harvest pattern with slightly more revenue in April and October reflecting the larger more valuable shrimp in the catch.

RESULTS

Results showing yield, revenue and NPV values from the optimization runs are presented in Table 5. Average annual landings for the model that optimized for NPV attained 5860 mt each year generating an average 53 mt per vessel per year or an average of 7.6 mt per month. Annual gross revenue and profit generated for the fleet under the NPV harvest strategy were $6.2 million and $1.6 million, respectively (Figure 6). The model did not explicitly account for fixed costs nor the opportunity costs for a vessel that chose not to fish for shrimp during the season. Rather, it relied on the harvesters' short-term decisions for profitability at the trip level. Net present value harvest patterns show low but consistent effort levels early in the season that gradually increased to take advantage of individual shrimp growth and associated higher ex-vessel price.

Table 2. Model Results and Extensions of the Oregon Ocean Shrimp Fishery

Model 22-year Optimization	**Utilization Landings (metric tons)**	**Income Revenue ($x1000)**	**Efficiency NPV ($x1000)**	**Comparison**
Sea Level Height/Stock Recruit Relation				
	145471.7	150352.5	40524.4	
Reduced Effort				
Sea Level Height/Stock Recruit Relation				Compare to SLHSR
100 vessel fleet	143507.2	148158.6	40041.3	-1.2%
80 vessel fleet	138475.2	142747.8	38775.6	-4.3%
60 vessel fleet	131048.1	135219.5	36889.6	-8.9%

[4] Pacific Fishing Information Network. 2004. PacFIN Web based Data. Pacific States Marine Fisheries Commission.

Shrimp count per pound (CPP) estimates are calculated from monthly shrimp catch composition. Annual average count per pound and ex-vessel prices from the model show the yearly trade-off between shrimp size and value to the fleet. Shrimp counts range from 70 to 136 shrimp per pound. Lower count per pound values correspond to years of poor shrimp abundance exhibiting higher ex-vessel prices. Opportunities for profit in years of lower abundance result in higher-than-average proportions of older shrimp in the catch. Similarly, years of high shrimp counts are a result of good shrimp recruitment but lead to lower shrimp prices.

Sea Level Height Environmental Variable and Preliminary Stock Recruit Relation

Outputs from the model that utilized the April sea level height and a preliminary stock recruit relationship (SLHSR) are found in Table 3. The NPV maximization generated average annual yields of 4983 metric tons of shrimp worth $5.1 million resulting in $1.4 million in discounted NPV for a 110-vessel fishery. Average per-vessel values generated 45 metric tons of shrimp. Shrimp ex-vessel value is worth $46,667 in gross revenue, providing each vessel with an average profit of $12,761. Fishery performance reflects the lower overall levels of inter season effort from fishery closures in four of the 22 years modeled.

The inclusion of spawner stock levels into optimization increased the level of shrimp to recruit to the stock by 24% but resulted in highly variable landings. The graph in Figure 4 shows annual recruits and fishery landings. Recruit numbers ranged from 0.5 to 9.0 billion with a higher overall average recruitment at 4.7 billion age 1 shrimp compared to the long-term average of the historical fishery at 3.7 billion. The model generated harvest patterns associated with periods of low fishing to allow the stock to increase to profitable levels before initiating effort and harvests. The fishery developed into a moderate volume fishery, reduced to a lower volume fishery by the El Niño event of 1982-83, and rebounded toward the end of the first decade. In the optimization, landings declined in 1992, following the 1990 El Niño, and subsequently resulted in lower effort and landings until the shrimp stock recovered from harvest and less favorable recruitment conditions (less than 3 billion shrimp recruits). Model landings ended the optimization horizon with extremely high variability.

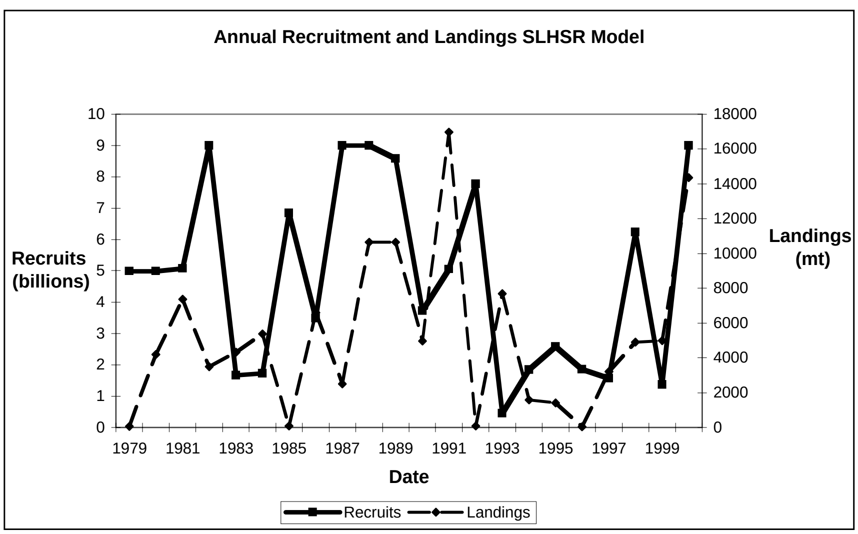

Figure 4. Sea Level Height Stock Recruit Model Recruitment and Landings – NPV Policy.

Spawning stock numbers are an integral part of the optimization model and provide an indication of the amount of spawning stock numbers necessary for long-term optimization of the fishery. The model presented explicitly considered the importance of spawning stock to future abundance. The model protects November spawning stock numbers by showing reduced fishing in late season months to generate better overall yield, revenue and NPV in the following year when age 2 shrimp contribute to the catch (as seen in Figure 2). November spawning stock numbers in the model averaged 2.68 billion. Implicit protection of the spawning stock numbers results in higher levels of end season (November) spawning stock that exceed the 1.3 billion spawner "threshold" level in six of the 22 years modeled.

Patterns of catch per unit effort, annual revenue and annual non-discounted profit (net revenue) for the SLHSR model extension are presented in Figure 5. The model attained an average CPUE value of 396 lbs./sre-h. This value is considerably higher than the 15-year historical average of 282 lbs./sre-h. The monthly average CPUE values from the model displayed reduced inter-seasonal variation from 202 to 780 lbs./sre-h.

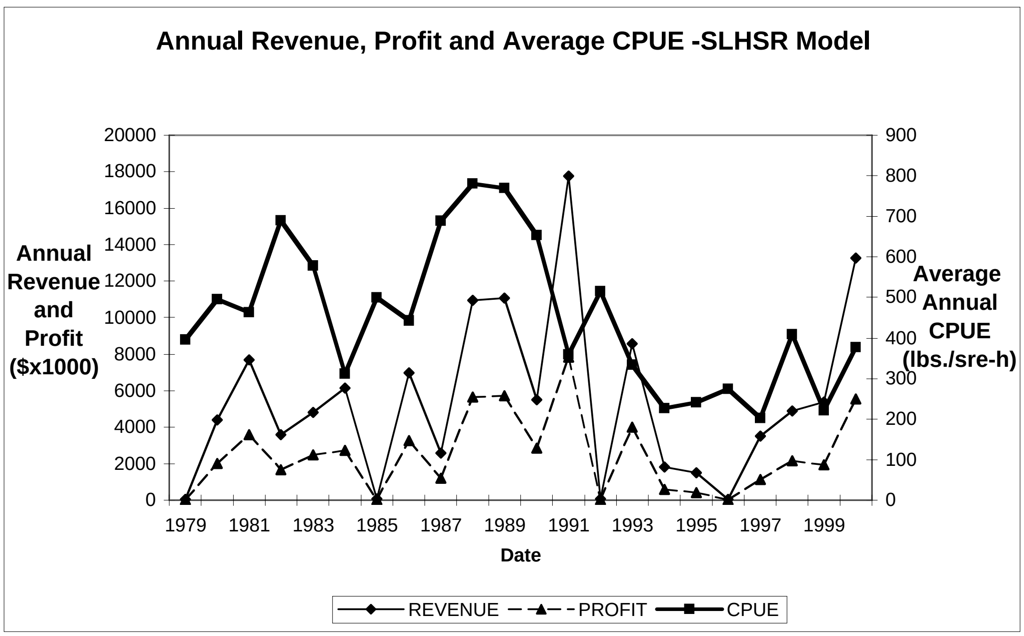

Figure 5. Annual Sum of Revenue Profit and Average CPUE

Reduced Effort in the Sea Level Height Stock Recruit Model Extension

Results from the model with systematic reductions in effort show showing output variables: yield, revenue and NPV. Comparisons of overall fishery landings to the 110-vessel fleet show 1-2% declines in catch, gross revenue and NPV as effort is reduced by 10%. Aggregated trip effort values show the impacts of model decisions such as trip costs and revenue that are made at an individual trip level. The 110-vessel model exhibited inter-annual fishery patterns that varied from zero to 2000 trips per year, averaging 555 trips per year. Fleet sizes of 80 and 60 vessels result in reductions in trip extremes generating average annual trip numbers of 519 and 481 trips per year, respectively. Intra-seasonal fishing patterns from the SLHSR optimization models show harvest patterns of early season pulse fishing. For all effort levels, high fishing effort in April and May target larger age 2 and 3+ shrimp, which are relatively more abundant early in the season. As fleet size is reduced to 60 vessels, the intra-seasonal variation declines to 25% of early season effort. An important benefit of reduced fleet effort can be found in the resulting reduction in inter- and intra- season variability of fishery performance measures.

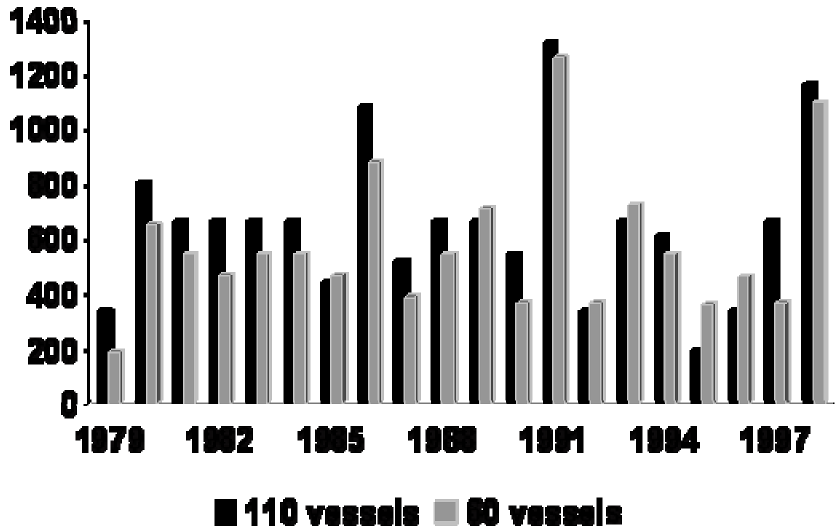

Figure 6. Seasonal trip numbers reflecting 110, 80 and 60 vessel fleet sizes – SLHSR Model.

DISCUSSION

Highly variable stocks that correlate with environmental variables typically show some strength in a stock recruit relationship at very low parent stock size. Ocean shrimp stock- recruit data also show a relationship at low stock sizes (Hannah, 1999). This paper presented an optimization model that incorporated an environmental variable and preliminary stock recruit relation generated relatively less variability in future recruits. The stock recruit relationship shows less explanatory power at higher stock sizes (above 4 billion shrimp) and must be constrained to generate recruitment less than 9.0 billion. The explanatory power of the environmental variable that determines future shrimp recruits is similar in both relationships and the statistical contribution of spawning stock is more prevalent at low stock sizes. This argument is consistent with Gulland (1983) who identified good, average and poor environmental conditions to separate the density dependent (low parent stock) and density independent (high parent stock) regions of the stock recruitment curve for marine resources. Despite a strong statistical relationship, given the historical data series there is no definitive evidence that the relationship of April Sea Level height and the quantity of age 2 and 3 shrimp would be highly predictive for future conditions.

Myers (1998) suggested that however important an environmental variable, it is not the key to good fishery management. Environment recruitment correlations will only have the power to enhance management for as long as the underlying relationship remains valid (Agnew, Beddington and Hill, 2002). The level of ocean shrimp catch in any particular year is determined largely by environmental factors (a good year class from favorable oceanographic conditions) and management decisions have only a minor effect. Myers (1998) warranted caution in the belief that previously published environment recruit relations would hold true using updated information. The environmental variable used in this paper and developed in 1993 continues to be a useful predictor of future recruitment in ocean shrimp. The extensive contrast of shrimp abundance and environmental conditions in the 22-year time series poses a low risk of time-series biases and autocorrelation in recruitment (Hilborn and Walters, 1992), providing evidence for the assumption that any stock recruit relationship is not spurious (Garcia, 1983).

Management strategies based on recruitment prediction instead of relying on fishery historical data show promise (Agnew, Beddington and Hill, 2002). Varying effort using an environmental correlate of recruitment can reduce the risk of not meeting conservation targets while increasing yield. Costello et al. (2001) found that predictions of poor environmental performance should lead to conservative resource management, but a prediction of poor environmental conditions means that expected future stock would be depressed and lower harvests can mitigate this effect.

This paper expanded the use of an optimization model by incorporating empirical information to evaluate management for a highly variable, environmentally driven ocean shrimp fishery. This research is a first attempt to specifically consider measurable environmental data to predict future shrimp recruitment. Model extensions explored harvest policies that could identify optimal harvest strategies in years when shrimp abundance was high while considering the impacts on future stocks. The economic consequences of overfishing are of particular interest to fishery management when shrimp size is large and shrimp ex-vessel prices relatively high, which are observed in years of low shrimp abundance.

Participation in the ocean shrimp fishery is expected to fluctuate but a lower level of effort can be effective in reducing catch variability. Reduced effort plus a spawner threshold may help stabilize the fishery by allowing age 2 and 3+ shrimp to dominate the fishery. A fishery with a substantial biomass will be less sensitive to environmental perturbations causing variations in recruits. Hannesson (1993) investigated the economic desirability of stabilizing catch versus fishing effort and concluded that stable effort is more profitable than stable catch unless the price of fish is dependent on the volume. Despite efforts to achieve stability in the variable ocean shrimp fishery, the most effective way to generate stable patterns of effort is to reduce overall effort. Oregon ocean shrimp contribute only 0.2% of the world shrimp production in any year[5]. Comparable substitutes for this fishery are abundant from Alaska, British Columbia, Eastern Canada and the Gulf of Maine. Any economic objectives that will support policies aimed at reducing year-to-year fluctuations and improve economic returns to fishermen may benefit the fishery in the long term.

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